Study on a Simple Evaluation Method of Urban Heat Island Mitigation Technology using Upper Weather Data

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ABSTRACT

The upper weather data recorded at four towers located between Osaka city and eastern Osaka city indicate that the sensible heat flux released in the urban canopy layer causes the surface air temperature to rise. Methods based on the surface–boundary layer model are used for estimating the amount of sensible heat flux released and the coefficient of heat transfer from surface air to upper air by convection. The convection heat transfer coefficient, changes in the air temperature with the release of sensible heat flux, and decrease in the air temperature due to the implementation of urban heat island mitigation strategies are estimated by using the observation data recorded at the four towers. The deviation in the convection heat transfer coefficient of the surface–boundary layer model over a decade and across the four towers is almost negligible. The difference between the air temperatures in the daytime and nighttime changes by a factor of two or three with the change in the amount of sensible heat flux released.

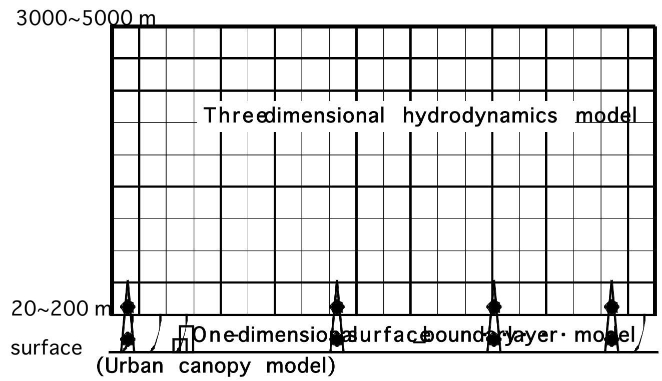
Introduction

In Japan, the urban heat island phenomenon, i.e., increased air temperature, that occurs in the urban area has been recognized to be a serious problem. Various urban heat island mitigation strategies are developed, and their effectiveness is determined by using them in various applications, for example, cool roofs, green roofs, cool pavements, HVAC systems, etc. Further, the characteristic of each technology have been clear (AIJ 2007; Takebayashi & Moriyama 2007). However, an evaluation method for the effectiveness of these mitigation strategies has not been established; thus, there are only a few examples of the implementation of mitigation strategies for the urban heat island phenomenon. Therefore, it is necessary to develop an evaluation method for mitigation strategies so that the residents and industries of Japan can make further technological advancements by implementing these strategies. In general, the evaluation of the effectiveness of urban heat island mitigation strategies is carried out by using meso- or small-scale numerical weather simulation models (Taha 1997). However, it is difficult to carry out numerical simulations for each strategy. The purpose of this study is to develop a simple evaluation method for the effectiveness of urban heat island mitigation strategies.

In the mesoscale weather simulation model, which is used for evaluating the effectiveness of urban heat island mitigation strategies, the upper layer of the one-dimensional surface–boundary layer model is coupled with the lower layer of the three-dimensional hydrodynamic turbulence model (University Corporation for Atmospheric Research; WRF Community). By estimating the heat budget of the ground surface, the amount of fluxes released into the atmosphere (a three-dimensional hydrodynamics model), such as momentum, heat, and moisture fluxes, is estimated. Recently, an urban canopy model is incorporated in the surface–boundary layer model for precise estimation of the amount of fluxes (Masson 2000; Kusaka, Kondo, Kikegawa & Kimura 2001; Kondo, Genchi, Kikegawa, Ohashi, Yoshikado & Komiyama 2005).

The structure of the mesoscale weather simulation model, which consists of the three-dimensional hydrodynamics model and the surface–boundary layer model, is shown in figure 1. The surface air temperature and wind velocity are calculated using the one-dimensional surface–boundary layer model; then, these results are set as the upper boundary condition of the three-dimensional hydrodynamics model and the amount of sensible heat flux released, which is estimated from the surface heat budget of the ground surface, is set as the lower boundary condition. Therefore, if we can obtain the upper weather data across the entire calculation domain, we can calculate the surface air temperature and wind velocity by using only the one-dimensional surface–boundary model with precision similar to that of general mesoscale weather simulation models. This method is simple, i.e., it does not require three-dimensional calculations. In fact, it is difficult to acquire the upper weather data with a high space resolution; in this study, we acquire the upper weather data at four observation points.

Figure 1. Structure of General Mesoscale Weather Simulation Model



In this study, as shown in figure 1, the upper boundary condition of the surface–boundary layer model, in other words, the lower boundary condition of the three-dimensional hydrodynamics model, is obtained directly. We install observation instruments on four steel towers with the cooperation of an electric power company and a phone company. The instruments are set from the west end to the east end of Osaka plains. Observation data recorded by the instruments are used for calculating the upper boundary condition of the surface–boundary layer model, and the change in the surface air temperature with the change in the amount of sensible heat flux released is particularly examined.

The relative location and distance of the four steel towers is shown in figure 2, and images of the observation instruments are shown in figure 3. The wind direction and velocity are recorded using a two-dimensional ultrasonic anemometer. The air temperature is measured using a thermistor-type thermometer. The observation period is 10 min. Nanko is a coastal area, Namba is an urban area, and Aramoto and Ishikiri are suburbs. Ishikiri is located at the foot of Mt. Ikoma. Each observation instrument is installed on the south side of the steel tower for reducing the effect of land and sea breeze on the tower, flowing in the east–west direction in the summer. The observation instruments have photovoltaic panels, a battery, and a data storage device. The data is transmitted via wireless communication at the ground level. Further, we use ten years' data collected at the Osaka tower, which is located in Osaka city, to account for secular variations. It is located in the urban area, and its distance from the seashore is the same as that of the Namba tower.

Figure 2. Location and Distance of Towers used for Upper Weather Observation

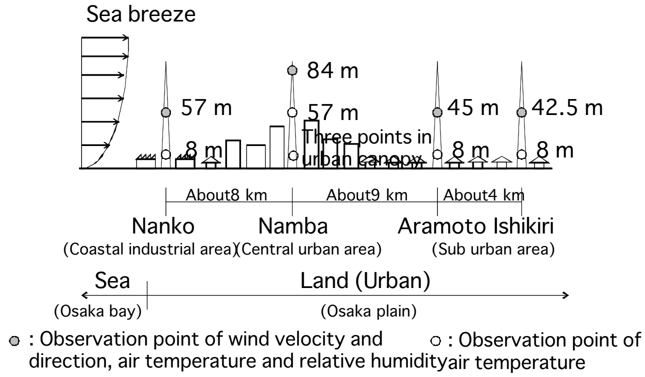
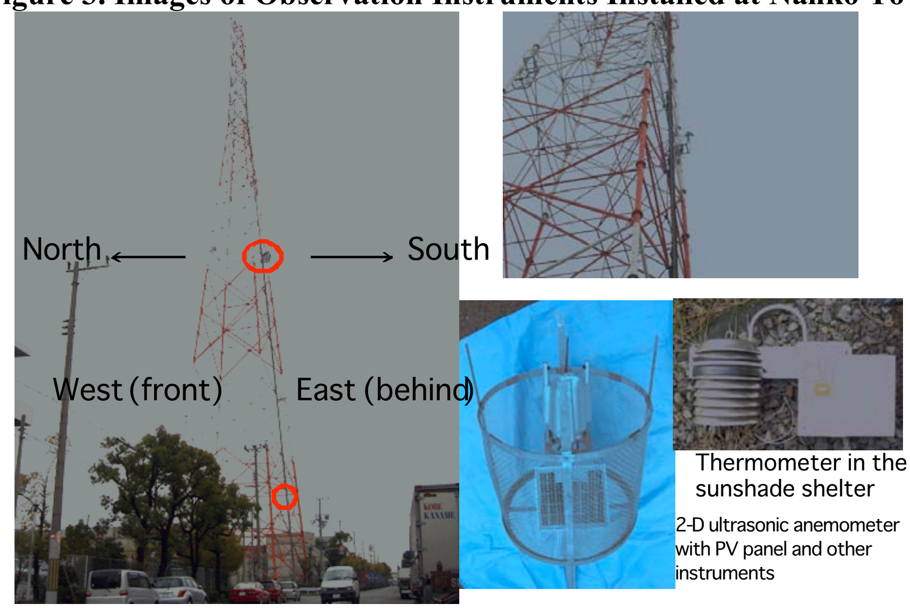


Figure 3. Images of Observation Instruments Installed at Nanko Tower



Outline of Surface–Boundary Layer Model

The sensible heat flux in the one-dimensional surface–boundary layer model is defined as shown in (1).

$$V = \alpha_c(\theta_0 - \theta_a) \qquad (1)$$

Here, V is the sensible heat flux (W/m^2); α_c, convection heat transfer coefficient (W/m^{2}K); θ_0, surface air potential temperature (K); and θ_a, upper air potential temperature (K).

The convection heat transfer coefficient is expressed as shown in (2) on the basis of the Monin–Obukhov similarity theory.

$$\alpha_c = \gamma C_p k^2 u_a / F_m F_a \qquad (2)$$

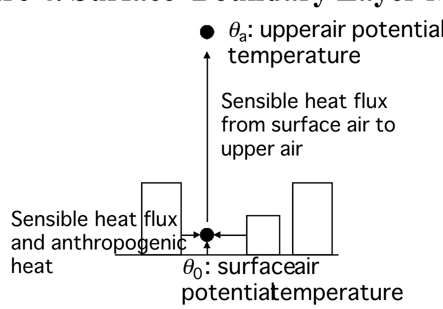
where C_p is the specific heat of air (= 1.0 kJ/kgK); γ, density of air (= 1.2 kg/m^3); k, von Karman constant (= 0.35); and u_a, upper wind velocity (m/s). F_m and F_h are integral values of the universal function (-). Businger's experimental expressions are used for the universal function.

It is noted that this similarity theory can be effectively used for explaining heat transportation phenomenon in urban areas (Moriwaki & Kanda 2006). However, in the case of unstable weather conditions, the constant flux layer is not formed. Since the similarity theory is generally used in mesoscale weather simulation models and the main purpose of this study is to develop a simple evaluation method for the effectiveness of urban heat island mitigation strategies, we use this similarity theory, although it has certain limitations.

Parameters used in this model are the upper wind velocity u_a, roughness parameter z_0, and difference in the upper and surface air potential temperatures θ_0–θ_a. The upper wind velocity and the upper and surface air potential temperatures are measured at the steel towers, and z_0 is assumed to be 1.5 m. α_c is estimated using the above mentioned parameters. Some estimation methods for z_0 are suggested, for example, using geometric characteristics such as building height and density and turbulence statistics such as friction speed, but, in this study, it is assumed according to previous studies (Moriyama & Takebayashi 1999).

An outline of the surface–boundary layer model is shown in figure 4. The sensible heat flux released from buildings and roads and the anthropogenic heat released from buildings and cars are discharged into the surface air, and the heat is transported to the upper air. When the amount of sensible heat flux and anthropogenic heat released is small, the change in the surface air temperature is small. When the amount of heat flux transported to the upper air is large, in the other words, when the heat does not remain in the surface air, the change in the surface air temperature is again small.

Figure 4. Surface–Boundary Layer Model

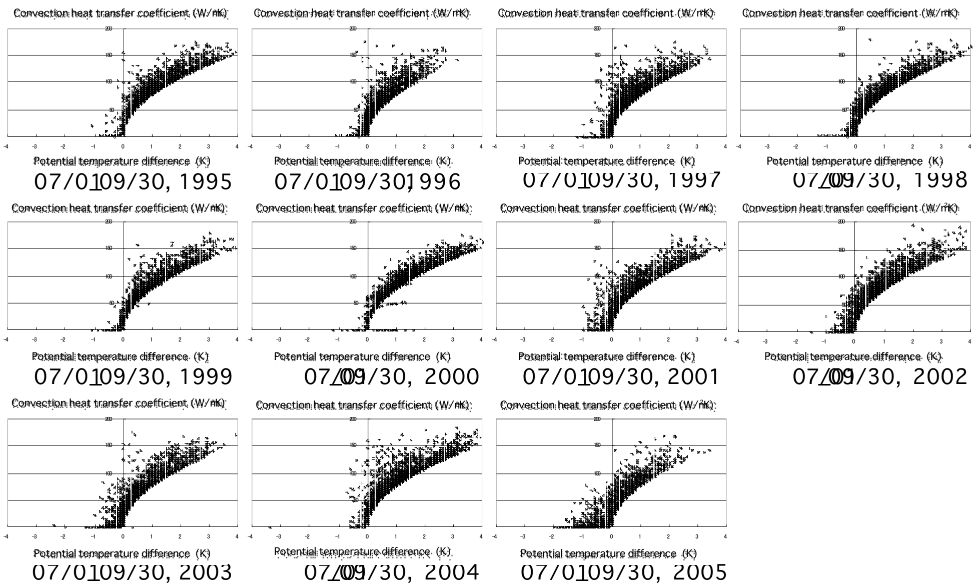


Convection Heat Transfer Coefficient Estimated using Upper Observation Data

Change in Convection Heat Transfer Coefficient Estimated using Observation Data Recorded at Osaka Tower

The convection heat transfer coefficient is estimated by using the wind velocity and upper air potential temperature measured at the Osaka tower. The surface air potential temperature is measured at the air pollution monitoring station of Osaka city at an observation point located at a height of 120 m above the ground level. The potential temperature of the neighboring area is recorded at an observation point located approximately 2 m above the roof of the building, i.e., at the bottom of the Osaka tower. Estimation results are shown in figure 4. All data from July to September are used in the analysis in order to consider the average summer conditions. The observation point at which the surface air potential temperature is measured was transferred in 1997 from the Tenma Junior High School to the Saibi Elementary School; however, both the observation points are located close to the Osaka tower, and the observation results of the air temperature show almost the same tendency. As shown in figure 5, the deviation in the convection heat transfer coefficient over the decade is almost negligible.

Figure 5. Difference Between Upper and Surface Air Potential Temperatures (x-axis) and Convection Heat Transfer Coefficient (y-axis) Estimated using Observation Data Recorded at Osaka Tower

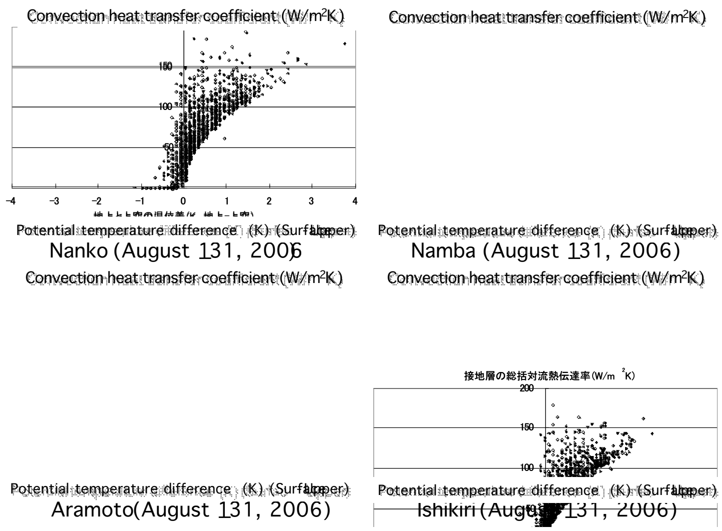


Convection Heat Transfer Coefficient Estimated using Observation Data Recorded at Four Towers

The convection heat transfer coefficient is estimated using the wind velocity and upper air potential temperature measured at the four towers and the surface air potential temperature measured below the Osaka tower, as shown in figure 6. The month of August is selected as the examination period, because the rainy season continues until the end of July. It is approximately similar to the result used observation data at Osaka tower. The difference between the upper and surface air potential temperatures is small at the Nanko tower; however, the convection heat transfer coefficient is comparatively high. The reason for this is considered to be the large wind velocity in the coastal area.

The difference between the upper and surface air potential temperatures measured at the four towers is smaller than that between the potential temperatures measured at the Osaka tower. The reason for this is believed to be the difference in the ground surface temperature recorded at these towers. The observation points, at which the surface air potential temperature is recorded, are located at a small distance from the ground surface below the four towers, but the distance of the observation point located below the Osaka tower is only 2 m from the top of the building roof. The observation instruments are installed close to the roofs of the buildings where the four towers are located. Since the Namba tower is located in the downtown area, we set three instruments on telephone poles located in the urban area, and the average of the surface air potential temperatures recorded by the three instruments is used as the surface air potential temperature in Namba.

Figure 6. Difference between Upper and Surface Air Potential Temperatures (x-axis) and Convection Heat Transfer Coefficient (y-axis) Estimated using Observation Data Recorded at Four Towers



Examination of Changes in Surface Air Temperature with Convection Heat Transfer Coefficient

Examination of Observation Data Recorded at Osaka Tower

The hourly mean values and standard deviations in the convection heat transfer coefficient from July 1 to September 30, which are estimated by the above mentioned method using the observation data recorded at the Osaka tower, are shown in figures 7 and 8. The convection heat transfer coefficient is approximately 100 W/m^{2}K in the daytime and approximately 50 W/m^{2}K in the nighttime. Thus, the standard deviation is large. The mean value is approximately 50 W/m^{2}K in the nighttime, and the standard deviation is approximately 30 W/m^{2}K. Thus, the standard deviation depends greatly on the climatic conditions.

The change in the surface air temperature $\Delta\theta$ (K), when additional amount of sensible heat flux ΔV (W/m^2) is released into the surface air, is estimated. In this case, the sensible heat flux transported from the surface air to the upper air is expressed as shown in (3).

$$V + \Delta V = \alpha_c' \{(\theta_0 + \Delta\theta) - \theta_a\} \qquad (3)$$

where $\Delta\theta$ causes α_c to change to α_c'. Thus, it is necessary to recalculate α_c' by convergence calculation. However, if $\Delta V < V$, $\alpha_c' = \alpha_c$. Then, (4) can be derived from (1) and (3).

$$\Delta\theta = \Delta V / \alpha_c \qquad (4)$$

In this study, evaluation of the effectiveness of heat island mitigation strategies is carried out by assuming that ΔV takes a negative value and $\alpha_c' < \alpha_c$. Therefore, (4) gives an underestimate of $\Delta\theta$, implying that the evaluation is incorrect. However, (4) is adopted in this study because it simplifies calculations.

Figure 7. Hourly Mean Values of Convection Heat Transfer Coefficient Recorded at Osaka Tower from July 1 to September 31

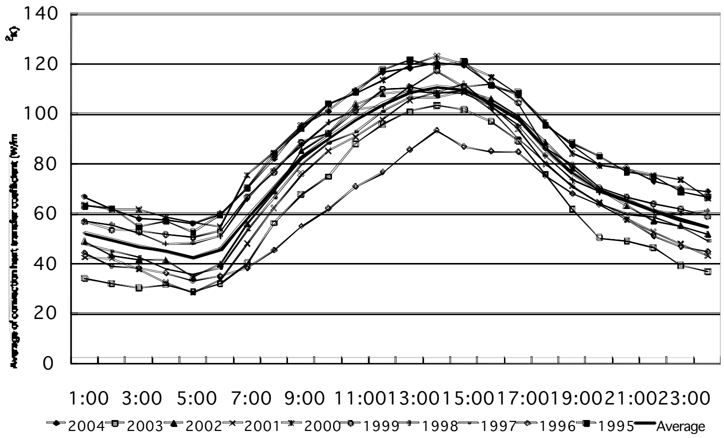


Figure 8. Standard Deviations in Convection Heat Transfer Coefficient Recorded at Osaka Tower from July 1 to September 31

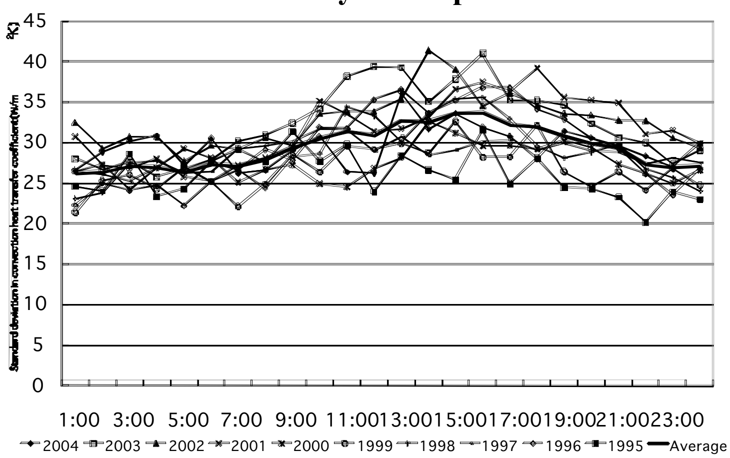
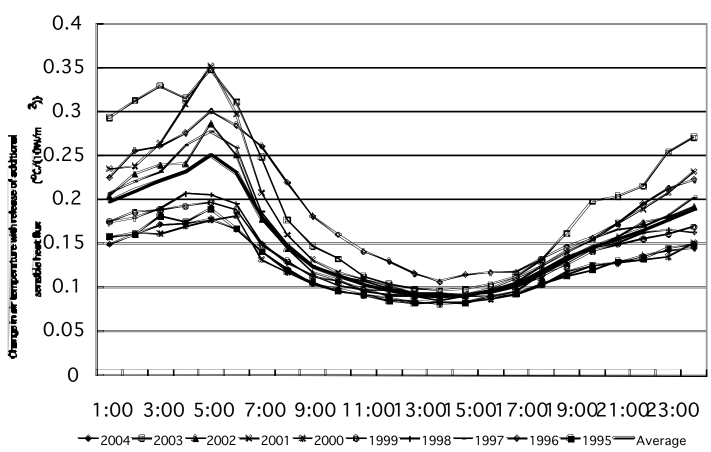


Figure 9. Change in Air Temperature with Release of Additional Sensible Heat Flux of 10 W/m^2



The change in the surface air temperature, estimated from (4) using the convection heat transfer coefficient shown in figure 7, when additional sensible heat flux of 10 W/m^2 is released into the surface air is shown in figure 9. When the convection heat transfer coefficient is small, the change in the surface air temperature is large. For the same amount of additional sensible heat flux released, the difference between the surface air temperature in the daytime and nighttime changes by a factor of two or three. However, because the standard deviation in the convection heat transfer coefficient is large in the nighttime, i.e., the average convection heat transfer coefficient of 50 W/m^2K changes to 20 W/m^2K, $\Delta\theta$ increases from 0.2° $C/10W/m^2$ to 0.5°$C/10W/m^2$. In the nighttime, it may be said that the surface air temperature increases greatly with a small change in the additional sensible heat flux released because the atmosphere is unstable.

Examination of Observation Data Recorded at Four Towers

The hourly mean values and standard deviations in the convection heat transfer coefficient, which are estimated by the above mentioned method using the observation data recorded at the four towers, are shown in figures 10 and 11. A comparison of the hourly mean values recorded at the Osaka tower over the decade shows that the change in the surface air temperature in Namba is small in the morning. The reason for this is considered to be the small difference between the upper and surface air potential temperatures recorded at this observation point than that between the temperatures recorded at the other observation points. In the daytime, sea breeze blows into the urban area, which makes the climatic conditions unstable, and therefore, a constant flux layer may not be formed. It is believed that heat is transported due to relatively large-scale turbulence in the sea breeze under this condition. The standard deviation in the convection heat transfer coefficient over the decade is almost equal to that estimated using the observation data recorded at the Osaka tower, but its value is large because the number of sampled data are few.

The change in the surface air temperature with the convection heat transfer coefficient is shown in figure 12a. It is assumed that the lowest value of the convection heat transfer coefficient is 1 W/m^2K. The tendency for the coefficient to be small in the daytime and large in the nighttime is clear, but the deviation is large. To avoid bad weather conditions from affecting the calculations, a fine weather day, i.e., a day with incident solar radiation of 12 MJ/m^2 and no precipitation is selected. The calculation result in the case of the fine weather day is shown in figure 12b. The deviation is still large. It is considered that the standard deviation in the convection heat transfer rate coefficient due to the release of a certain amount of additional sensible heat flux is almost zero. The lowest value of the convection heat transfer coefficient is assumed to be 10 W/m^2K, as shown in figure 12c. In the case of stable climatic conditions, calculating the changes in the surface air temperature with the convection heat transfer coefficient is difficult.

The surface air temperature increases by approximately 0.1°C in the daytime and approximately 0.2–0.3°C in the nighttime with the release of additional sensible heat flux of 10 W/m^2. This result is similar to that observed in the case of the data recorded at the Osaka tower. The temperature recorded at the four steel towers rarely changes; however, that recorded at the Namba tower changes greatly in the morning on the fine weather day. The change in the hourly mean values of the upper and surface air potential temperatures from August 1 to 31, 2006, is shown in figure 12. The difference between the upper and surface air potential temperatures recorded at the Nanko tower and that recorded at the other observation points is approximately 2°C in the daytime. However, this difference is small in the nighttime. The change in both the upper and surface air potential temperatures is regulated by the sea breeze blowing into Nanko, which is a coastal area. As a result, the difference in the upper and surface air potential temperatures in the coastal area is almost equal to that in the potential temperatures in the inland area. Thus, the convection heat transfer coefficients estimated at all the observation points are almost equal.

Figure 10. Hourly Mean Values of Convection Heat Transfer Coefficient Recorded at Four Towers and Osaka Tower from August 1 to 31

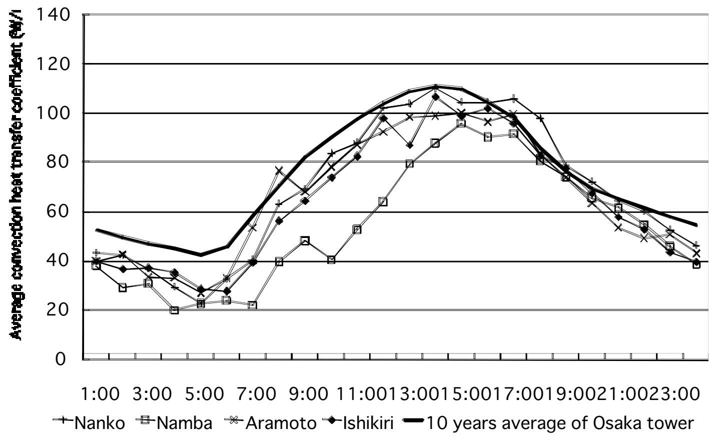
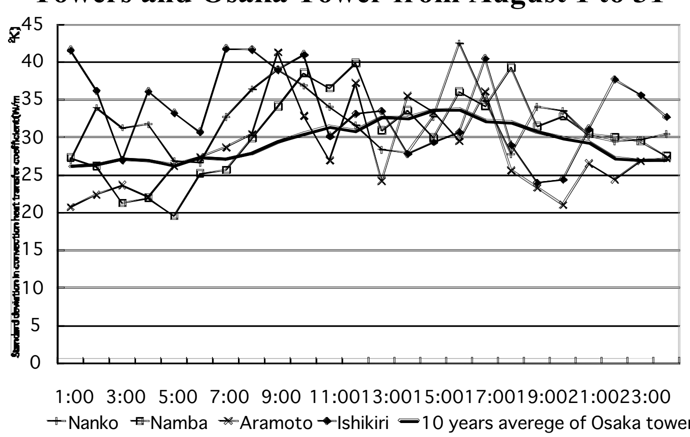


Figure 11. Standard Deviations in Convection Heat Transfer Coefficient Recorded at Four Towers and Osaka Tower from August 1 to 31



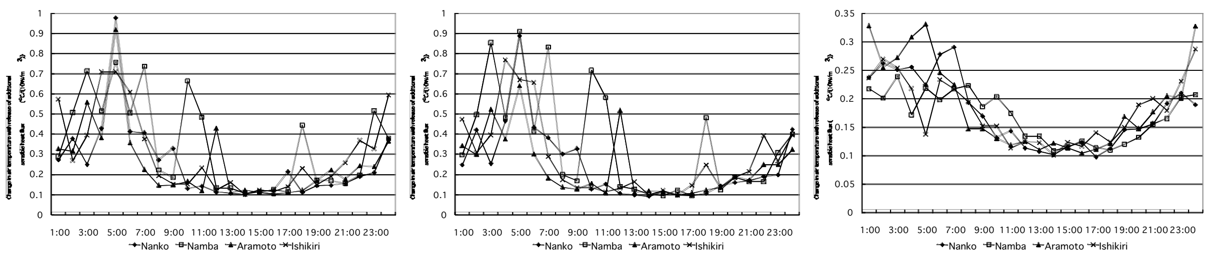
Evaluation of Effectiveness of Urban Heat Island Mitigation Strategies in Decreasing Surface Air Temperature

Urban heat island mitigation strategies are implemented and their effectiveness is evaluated by estimating the decrease in the surface air temperature by the above mentioned method. Urban heat island mitigation strategies implemented on buildings and road surface coatings are selected. Parameters are set according to previous studies, as shown in table 1 (Takebayashi & Moriyama 2007). The sensible heat flux released from the surfaces, where urban heat island mitigation strategies are implemented, is calculated by using the surface heat budget model. The changes in the surface air temperature and amount of sensible heat flux released are shown in figure 12. The base condition is assumed to be consisted of concrete surface 60% and asphalt surface 40%.

The decrease in the amount of sensible heat flux released is calculated by assuming that the urban heat island mitigation strategy is implemented on all types of concrete surfaces (i.e., green roofs, white cool roofs, gray cool roofs) or all types of asphalt surfaces (i.e., water keeping asphalt, water keeping concrete, water keeping block). But the relationship between each other building that means the sunshade, mutual radiation exchange is not considered here.

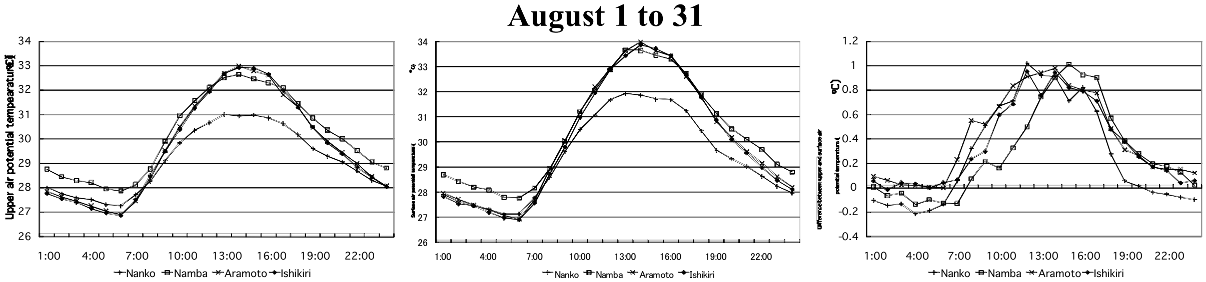
The sensible heat flux released from each of the above mentioned surfaces in the day- and nighttime is estimated, and the results are shown in table 2. The decrease in the surface air temperature is calculated by estimating the decrease in the sensible heat flux released from each surface and changes in the surface air temperature with the release of additional sensible heat flux. The reduced surface air temperatures recorded at the Nanko (coastal) and Namba (urban) towers are shown in tables 3 and 4. Because the effect of the mitigation strategies in reducing the amount of sensible heat flux released is small in the nighttime, the decrease in the surface air temperature is small, too. If 10 W/m^2 of anthropogenic heat is reduced uniformly in the nighttime, the surface air temperature is reduced by 0.21°C in Nanko and by 0.19°C in Namba.

Figure 12. Change in Surface Air Temperature with Release of Additional Sensible Heat Flux of 10 W/m^2



a. Data collected on all days, b. Data collected on fine weather day, c. Data collected with lower limit of convection heat transfer coefficient set at 10 W/m^2K

Figure 13. Hourly Mean Values of Observation Results Recorded at Four Towers from August 1 to 31



a. Upper air potential temperature, b. Surface air potential temperature, c. Difference between upper and surface air potential temperatures

Table 1. Parameters of surface heat budget model

	Asphalt	Concrete	Green roof	White cool roof	Gray cool roof	Water keeping asphalt	Water keeping concrete	Water keeping block
Albedo (-)	0.044	0.357	0.15	0.74	0.36	0.37	0.153	0.233
Evaporative efficiency (-)	0	0	0.14	0	0	0.084	0.029	0.035
Thermal conductivity (W/mK)	0.84	1.59	0.6	1.59	1.59	0.87	0.99	0.65
Thermal capacity (J/m^3K)	700000	100000	2900000	100000	100000	1500000	500000	30000

Table 2. Estimation Results of Sensible Heat Flux Released in Night- and Daytime

W/m^2	Green roof	White cool roof	Gray cool roof	Water keeping asphalt	Water keeping concrete	Water keeping block
Daytime	34.5	92.6	0.73	30.1	11.2	11.0
Nighttime	4.21	0.58	0.00	2.57	1.02	1.10

Table 3. Reduced Surface Air Temperature Recorded at Nanko Tower (Coastal)

°C	Green roof	White cool roof	Gray cool roof	Water keeping asphalt	Water keeping concrete	Water keeping block
Daytime	0.42	1.19	0.01	0.38	0.14	0.13
Nighttime	0.08	0.01	0.00	0.05	0.02	0.02

Table 4. Reduced Surface Air Temperature Recorded at Namba Tower (Urban)

°C	Green roof	White cool roof	Gray cool roof	Water keeping asphalt	Water keeping concrete	Water keeping block
Daytime	0.48	1.37	0.01	0.43	0.16	0.15
Nighttime	0.07	0.01	0.00	0.04	0.02	0.02

Conclusion

The upper weather data recorded at four towers located between Osaka city and eastern Osaka city indicate that the sensible heat flux released into the urban canopy layer causes the surface air temperature to rise. Methods based on the surface–boundary layer model are used for estimating the amount of sensible heat flux released and the coefficient of heat transfer from surface air to upper air by convection.

The convection heat transfer coefficient estimated at the Osaka and the four towers show that the standard deviation in the coefficient over a decade and across the four towers is almost negligible.

Even if the difference in the upper and surface air potential temperatures is small, the convection heat transfer coefficient estimated at the Nanko tower (coastal) is confirmed to be large because of the high wind velocity associated with sea breeze. The convection heat transfer coefficient estimated at the Namba tower (urban) is less than that estimated at the other observation points in the morning, because sea breeze blows inland during this time and climatic conditions become unstable.

The change in the surface air temperature with the release of additional sensible heat flux into the surface air is estimated using the convection heat transfer coefficient. The difference between the air temperatures in the daytime and nighttime changes by a factor of two or three when the amount of additional sensible heat flux released is the same. Because the atmosphere is unstable in the nighttime, the surface air temperature changes greatly with the release of additional sensible heat flux.

Urban heat island mitigation strategies are implemented and their effectiveness is evaluated by estimating the decrease in the surface air temperature in the night - and daytime. The above mentioned method can be used to evaluate the effectiveness of urban heat island mitigation strategies not only by estimating the amount of sensible heat flux released from buildings and pavement surface coating systems but also by estimating the decrease in the amount of anthropogenic heat released.

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